Medium Modification of Jet Shapes and Jet Multiplicities

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Medium-induced parton energy loss is widely considered to underly the suppression of high-p_t leading hadron spectra in $\sqrt{s_{\rm NN}} = 200$ GeV Au+Au collisions at RHIC. Its description implies a characteristic k_t-broadening of the subleading hadronic fragments associated to the hard parton. However, this latter effect is more difficult to measure and remained elusive so far. Here, we discuss how it affects genuine jet observables which are accessible at LHC and possibly at RHIC. We find that the k_t-broadening of jet multiplicity distributions provides a very sensitive probe of the properties of dense QCD matter, whereas the sensitivity of jet energy distributions is much weaker. In particular, the sensitive kinematic range of jet multiplicity distributions is almost unaffected by the high multiplicity background.

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Hard partons produced in dense QCD matter are expected to loose a significant fraction of their energy due to medium-induced gluon radiation prior to hadronization [1]. This follows from calculations of the underlying non-Abelian Landau-Pomeranchuk-Migdal effect and allows to predict the dependence of parton energy loss on pathlength and density in a static [2, 3, 4, 5] or expanding [6, 7, 8] medium. Recent measurements [9] of high-p_t hadroproduction and its centrality dependence in Au-Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV provide the first evidence [10] for the occurrence of this jet quenching phenomenon. They allow to access properties of the dense medium produced in nucleus-nucleus collisions by analyzing the medium modification of high-p_t hadroproduction [8, 11, 12].

So far, these analyzes are limited to the study of leading hadron spectra and leading hadron back-to-back correlations. However, energy loss of the leading parton implies a redistribution of the associated jet energy in transverse phase space or multiplicity. Thus, the observed energy degradation of leading hadrons should be reflected in the modification of genuine jet observables such as jet shapes and jet multiplicity distributions. The main aim of this letter is to calculate for the first time medium-modified jet observables in the same theoretical framework on which the current jet quenching interpretation of suppressed high-p_t hadroproduction is based.

We start from the k_t-differential medium-induced distribution of gluons of energy ω radiated off an initial hard parton [4, 13, 14],

$$\omega\frac{dI_{\rm med}}{d\omega\, d\mathbf{k}} = \frac{\alpha_s\, C_F}{(2\pi)^2\,\omega^2}\, 2{\rm Re}\int_0^\infty dy_l \int_{y_l}^\infty d\bar{y}_l \int d^2\mathbf{u}\; \times e^{-i\mathbf{k}_t\cdot\mathbf{u}}\, e^{-\frac{1}{2}\int_{\bar{y}_l}^\infty d\xi\, n(\xi)\,\sigma(\mathbf{u})}\, \frac{\partial}{\partial \mathbf{y}}\cdot\frac{\partial}{\partial \mathbf{u}} \times \int_{\mathbf{y}=\mathbf{r}(y_l)}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} \mathcal{D}\mathbf{r} \exp\left[i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2}\left(\dot{\mathbf{r}}^2 - \frac{n(\xi)\,\sigma(\mathbf{r})}{i\,2\,\omega}\right)\right]. \quad (1)$$

Medium properties enter (1) via the product of the medium density $n(\xi)$ of scattering centers times the dipole cross section $\sigma(\mathbf{r})$ which measures the interaction strength of a single elastic scattering. We first establish that Eq. (1) implies a one-to-one correspondence between the average energy loss of the parent parton, and the transverse momentum broadening of the associated gluon radiation, as argued in Ref. [2]. To this end, we evaluate $\omega\frac{dI_{\rm med}}{d\omega\, d\mathbf{k}}$ for $\alpha_s\, C_F = \frac{4}{9}$ in two approximations:

In the multiple soft scattering limit $n(\xi)\,\sigma(\mathbf{r}) \approx \frac{1}{2}\hat{q}(\xi)\,\mathbf{r}^2$, the transport coefficient $\hat{q}$ characterizes the average transverse momentum squared transferred from the medium to the projectile per unit pathlength. In this case, medium-induced gluon radiation is limited to gluon energies $\omega < \omega_c = \frac{1}{2}\,\hat{q}\,L^2$, see Fig. 1. In medium pathlength L and transport coefficient $\hat{q}$ determine not only the average energy loss of the leading parton, $\Delta E = \int d\omega\,\omega\frac{dI_{\rm med}}{d\omega} \sim \alpha_s\omega_c$, but also the typical transverse momentum transferred from the medium. This limits medium-induced gluon radiation to $\kappa^2 = \frac{\mathbf{k}^2}{\hat{q}\,L} < 1$.

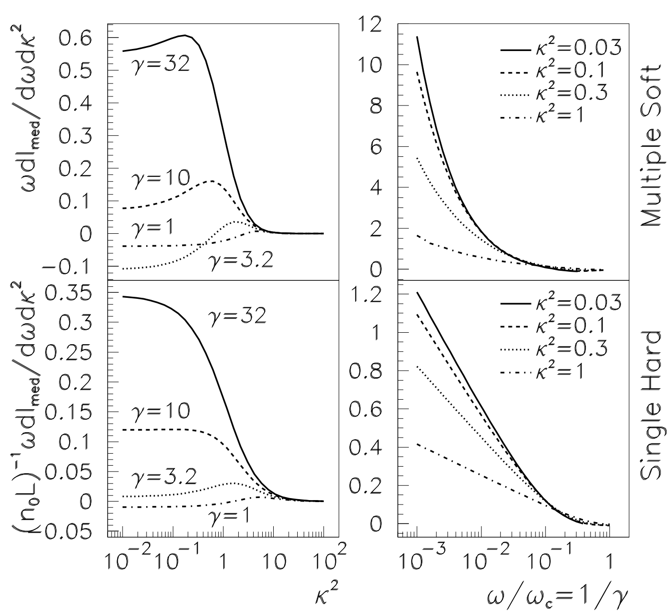

FIG. 1: The gluon energy distribution (1) as a function of the rescaled gluon energy ω/ω_c and the rescaled gluon transverse momentum κ.

The same conclusion is reached in the $N = 1$ opacity expansion of (1) in which the medium is characterized by the average transverse momentum μ per scattering times the average number $n_0\, L$ of such scatterings. In this case, the radiation is limited to a characteristic gluon energy $\omega_c = \frac{1}{2}\mu^2\, L$ and a typical transverse momentum $\kappa^2 = \frac{\mathbf{k}^2}{\mu^2}$. The opacity $n_0\, L$ can be adjusted such that both approximations give quantitatively comparable results for phase-space averaged quantities as e.g. the average energy loss [14]. Differences in the shape of the distributions shown in Fig. 1 are indicative of the uncertainties in modeling the detailed structure of the medium.

Next we ask to what extent the k_t-broadening of the medium-modified parton shower, established in Fig. 1, shows up in the azimuthal redistribution of jet energy. We start form the fraction $\rho(R)$ of the total jet energy E_t deposited within a given jet subcone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\Phi)^2}$,

$$\rho_{\rm vac}(R) \;=\; \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_t(R)}{E_t(R=1)}\,. \qquad (2)$$

In the absence of medium-effects, this jet shape is described e.g. by the parametrization [15] of the Fermilab $D0$ Collaboration for jets in the range $\approx 50 < E_t < 150$ GeV and opening cones $0.1 < R < 1.0$. In what follows, we work in the dijet center of mass where the jet width in pseudorapidity $\Delta\eta$ and azimuth $\Delta\Phi$ is related to the gluon emission angle Θ of our calculation as $R = \Theta$. To discuss the medium-dependence of $\rho(R)$, we calculate the probability $P_{\rm tot}(\epsilon,\Theta)$ that a fraction ϵ of the total jet energy E_t is emitted outside the angle Θ. Assuming that gluon emission follows an independent Poisson process, this probability is given by [16]

$$P_{\rm tot}(\epsilon,\Theta) = \int_C \frac{d\nu}{2\pi i}\, e^{\nu\,\epsilon} \times \exp\left[-\int_0^\infty d\omega \left(\frac{dI^{>\Theta}_{\rm vac}}{d\omega} + \frac{dI^{>\Theta}_{\rm med}}{d\omega}\right) \left(1 - e^{-\nu\omega}\right)\right], \qquad (3)$$

where the contour C goes along the imaginary axis. The expression (3) takes into account the angular energy distribution of the parton fragmentation process in the vacuum, $\frac{dI^{>\Theta}_{\rm vac}}{d\omega} = \int_\Theta^\pi d\varphi\, \frac{dI_{\rm vac}}{d\omega\, d\varphi}$, as well as its medium-modification $\frac{dI^{>\Theta}_{\rm med}}{d\omega}$ calculated from eq. (1). Since both contributions are additive, the total probability (3) can be written as a convolution of the vacuum and the medium-induced probability

$$P_{\rm tot}(\epsilon,\Theta) = \int d\epsilon_1\, P_{\rm vac}(\epsilon_1,\Theta)\, P_{\rm med}(\epsilon-\epsilon_1,\Theta)\,. \qquad (4)$$

We calculate the quenching weight $P_{\rm med}(\epsilon,\Theta)$ from eq. (1), see Ref. [14]. The vacuum contribution $P_{\rm vac}(\epsilon,\Theta)$ in (4) is determined by the experimentally measured jet shape $\rho_{\rm vac}(R)$, normalized to the vacuum fraction of the total jet energy

$$\int d\epsilon\, \epsilon\, P_{\rm vac}(\epsilon,\Theta) = \frac{E_t - \Delta E}{E_t}\left[1 - \rho_{\rm vac}(R=\Theta)\right]\,, \qquad (5)$$

where $\Delta E \equiv \Delta E(R=0) = \int d\epsilon \epsilon P_{\rm med}(\epsilon,\Theta=0)$. In the absence of tabulated experimental data on the width of $P_{\rm vac}(\epsilon,\Theta)$, we choose a sharply peaked distribution $P_{\rm vac}(\epsilon,\Theta) = \delta\left(\epsilon - \frac{E_t-\Delta E}{E_t}\left[1-\rho_{\rm vac}(R)\right]\right)|_{R=\Theta}$. The medium-modified jet shape $\rho_{\rm med}(R)$ is then defined in terms of the average jet energy fraction $\frac{\Delta E(\Theta)}{E_t}$ radiated outside an angle Θ,

$$\rho_{\rm med}(R) \equiv 1 - \int d\epsilon\, \epsilon\, P_{\rm tot}(\epsilon,\Theta=R) = \rho_{\rm vac}(R) - \frac{\Delta E_t(R)}{E_t} + \frac{\Delta E}{E_t}\left(1-\rho_{\rm vac}(R)\right)\,, \qquad (6)$$

We have calculated (6) as a function of the in-medium pathlength L, the jet energy E_t, and the transport coefficient $\hat{q}$. Numerical results are shown in Fig. 2. In the eikonal approximation, the quenching weight $P_{\rm med}(\epsilon,\Theta)$ is known to have support in the unphysical region $\epsilon > 1$ [14]. This introduces an uncertainty which we estimate with the shaded region in Fig. 2 by comparing the result of an unrestricted ϵ integration in (6), $\frac{\Delta E(\Theta)}{E_t}|_1 \equiv \int d\epsilon\, \epsilon\, P_{\rm med}(\epsilon,\Theta)$, to the properly reweighted restricted integration

$$\left.\frac{\Delta E(\Theta)}{E_t}\right|_2 = \frac{\int_0^1 d\epsilon\, \epsilon\, P_{\rm med}(\epsilon,\Theta)}{\int_0^1 d\epsilon\, P_{\rm med}(\epsilon,\Theta)}\,. \qquad (7)$$

In general, we find that the medium modification (6) grows approximately linear with the transport coefficient (data not shown) in agreement with the $\hat{q}$-dependence of the average energy loss $\Delta E(\Theta)$. The medium modification decreases approximately like $1/E_t$ with increasing jet energy. Qualitatively comparable results are obtained in the $N = 1$ opacity approximation (data not shown).

The parameter values chosen in Fig. 2 ($\omega_c = 62$ GeV, $\omega_c\, L = 2000$) amount to an average squared momentum transfer of $\hat{q}\, L \approx (2\,\mathrm{GeV})^2$ from the medium to the partonic jet components. This is a rough estimate for nucleus-nucleus collisions at the LHC and corresponds to an initial gluon density which is a factor ≈ 2 larger than values extracted from RHIC data [8]. The resulting medium-induced broadening of the jet shape shown in Fig. 2, amounts to a slightly reduced average jet energy fraction inside small jet cones $R = 0.3$ by ~ 5 % for $E_t = 50$ GeV and ~ 3 % for $E_t = 100$ GeV. Although somewhat larger initial gluon densities and thus larger medium modifications are conceivable at LHC, the size of the resulting modification remains small. For larger jet cones ($R > 0.7$ say), medium effects become even smaller since the medium-induced energy redistribution occurs mainly inside the jet cone. This may allow to

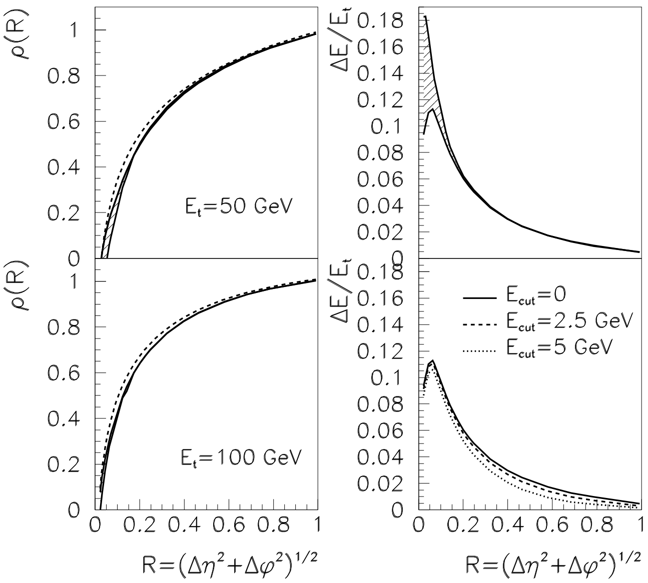

FIG. 2: LHS: The jet shape (2) for a 50 GeV and 100 GeV quark-lead jet which fragments in the vacuum (dashed curve) or in a dense QCD medium (solid curve) characterized by $\omega_c = 62$ GeV and $\omega_c\, L = 2000$. RHS: the corresponding average medium-induced energy loss for $E_t = 100$ GeV outside a jet cone R radiated away by gluons of energy larger than $E_{\rm cut}$. Shaded regions indicate theoretical uncertainties discussed in the text.

measure the total jet energy above background without resorting to jet samples "tagged" by a recoiling hard photon or Z-boson. It implies that jet E_t cross sections in nucleus-nucleus collisions scale with the number of binary collisions.

In nucleus-nucleus collisions at LHC, jets up to $E_t >$ 200 GeV will be produced abundantly [17]. However, the background $E_t^{\rm bg}$ deposited inside the corresponding jet cone (for event multiplicity $dN^{\rm ch}/dy = 2500$, we estimate $E_t^{\rm bg} \sim 100$ GeV for $R = 0.3$ and $E_t^{\rm bg} \sim 250$ GeV for $R = 0.5$) is of comparable size. Thus, it is feasible to disentangle a high-E_t jet from background, but the measurement of a < 10 % modification of its shape remains challenging. In particular, such precision may require a better theoretical understanding of how the initial state radiation associated to a high-E_t jet affects the underlying event and its fluctuations (the so-called pedestal effect).

Interestingly, the transverse momentum broadening shown in Fig. 2 changes only weakly with a low momentum cut-off which removes gluon emission below 5 GeV. This can be understood in terms of formation time and phase space limitations in a small-size medium [14]. As a consequence, the transverse momentum broadening of $\rho(R)$ is mainly due to high energy partons which can be expected to contribute significantly to the hadron yield above background. To study this point in more detail, we have calculated the medium-induced additional number of gluons with transverse momentum $k_t = |\mathbf{k}|$, produced within a subcone of opening angle θ_c,

$$\frac{dN_{\rm med}}{dk_t} = \int_{k_t/\sin\theta_c}^{E_t} d\omega\, \frac{dI_{\rm med}}{d\omega\, dk_t}\,. \tag{8}$$

In Fig. 3, we compare this distribution to the shape of the corresponding vacuum component, $\frac{dN_{\rm vac}}{dk_t} \propto \frac{1}{k_t}\log(E_t \sin\theta_c/k_t)$, calculated from eq. (1) as well. The total partonic jet multiplicity is the sum of both components. For realistic values of medium density and in-medium pathlength, medium effects are seen to increase this multiplicity significantly (by a factor $\sim 2-5$) in particular in the high-k_t tails. Also, the shape and width of the distribution (8) changes sensitively with the scattering properties of the medium. Moreover, since gluons must have a minimal energy $\omega > k_t/\sin\Theta_c$ to be emitted inside the jet cone, this high-k_t tail is unaffected by "background" cuts on the soft part of the spectrum, see Fig. 3. These qualitative conclusions are not affected by the uncertainties of our calculation which are illustrated by the significant differences in the angular dependence of the medium-induced gluon radiation (1) in the multiple soft and single hard scattering approximation [14]. In particular, destructive interference effects are known [13] to be more significant in the multiple soft scattering limit and for small angles, which may explain the non-monotonous behaviour seen for $\Theta_c = 0.3$ in Fig. 3.

On the basis of Fig. 3, we argue that the measurement of the transverse momentum distribution of hadrons with respect to the jet axis is very sensitive to the transverse momentum broadening of the underlying parton shower and should be detectable above background. Despite the expected enhancement in the high-k_t tail, the total multiplicity of a jet will increase and the average energy of the hadronic fragments will soften. Hadronization of the parton shower is known to affect the absolute size and shape of this multiplicity distribution in the vacuum [18] and can be expected to modify the medium-dependent part as well. Also, experimental effects such as an increased uncertainty in determining the jet axis in a high multiplicity environment tend to broaden the distribution and have to be taken into account properly. To become more quantitative on the level of hadronic observables requires presumably a Monte Carlo implementation of the medium-modified parton shower which is not at our disposal yet. However, the effect observed in Fig. 3 can be expected to survive hadronization. In particular, the insensitivity of the high-k_t tail to the low E_t background and its sensitivity to the transverse momentum picked up from the medium are both based on kinematic grounds and should not depend on the details of our calculation.

Other multiplicity distributions may show interesting medium modifications as well. As an example, we mention the modifications of the hump-backed rapidity

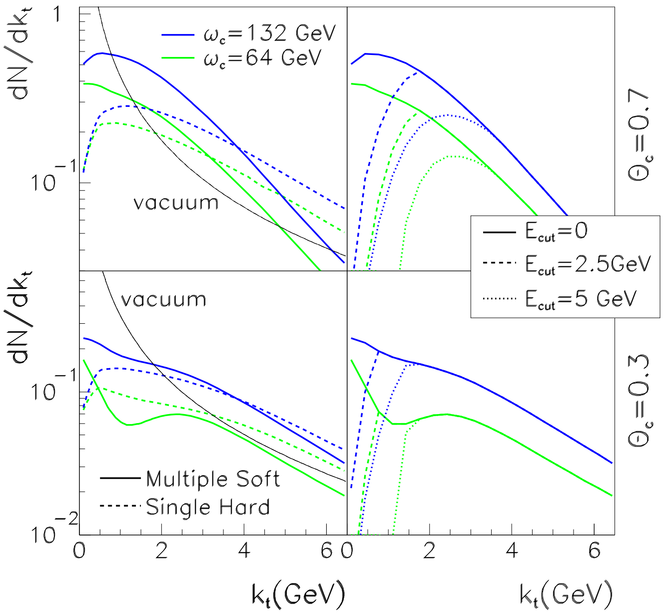

FIG. 3: Comparison of the vacuum and medium-induced part of the gluon multiplicity distribution (8) inside a cone size $R = \Theta_c$, measured as a function of k_t with respect to the jet axis. Removing gluons with energy smaller than $E_{\rm cut}$ from the distribution (dashed and dotted lines) does not affect the high-k_t tails.

plateau, i.e. the number of hadrons with jet energy fraction x inside the jet. In the vacuum, it is well-described by the result of the MLLA approximation which depends on the jet energy only via the parameter combination $\frac{E_t \sin\Theta_c}{Q_{\rm eff}}$ with $Q_{\rm eff} \sim 250\,{\rm MeV} \sim \Lambda_{\rm QCD}$ the only fit parameter [18]. The medium-modification of the corresponding partonic quantity is

$$\frac{dN_{\rm med}}{d\log x} = \int_0^{\frac{x\,E_t\,\sin\Theta_c}{\sqrt{\hat{q}L}}} d\kappa^2\, \frac{dI_{\rm med}}{d\log x\, d\kappa^2}\,. \tag{9}$$

Here, we only observe that the medium modification of $\frac{dN_{\rm med}}{d\log x}$ supplements the non-perturbative scale $Q_{\rm eff}$ with a perturbatively large scale $\sqrt{\hat{q}L} \sim Q_s$. A more detailed analysis of (9) and other multiplicity distributions is left to future work.

We finally comment on the implications of our study for the ongoing experiments at RHIC. In general, the strategy of triggering on the most energetic hadron biases jet samples significantly and may deplete in particular the multiplicity of subleading high-momentum hadrons. Furthermore, if the energy of the leading particle is not sufficiently high, the transverse phase space mapped out in Fig. 3 is simply not available. However, our study points to the possibility that a significant increase in jet multiplicity (and hence a decrease of the average energy of the leading hadron inside the jet) is accompanied by a rather moderate change in the angular distribution of the jet energy flow. This may be tested at RHIC e.g. by measuring in back-to-back dihadron correlations the total E_t (or multiplicity) in a cone around the triggered hadron as well as the balancing energy in the opposite direction, and subtracting the background energy $E_t^{\rm bg}$.

In summary, while k_t-broadening in the initial [19] and final [20] state has been discussed repeatedly for leading hadron spectra, the observables studied here relate this broadening quantitatively to parton energy loss. Their measurement would not only further substantiate the picture of a medium-modified parton shower which underlies the current jet quenching interpretation of high-p_t hadroproduction. Compared to leading hadron spectra, the k_t-broadening of multiplicity distributions may also provide data of competing accuracy for a better tomographic characterization of dense QCD matter.

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